Low aspect ratio plasma in tokamak-helical hybrid device TOKASTAR-2

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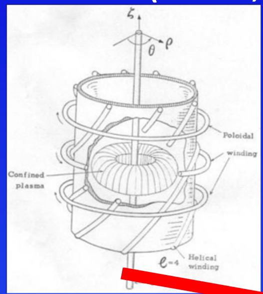
1. Introduction: Low aspect-ratio helical system

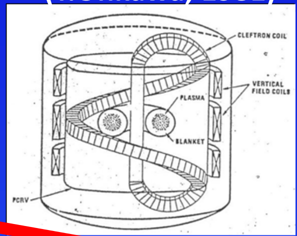
K. Yamazaki *et al.*, Journal of Plasma and Fusion Research SERIES **8**, 1044 (2009)

Non-Axisymmetric Shaping Proposals

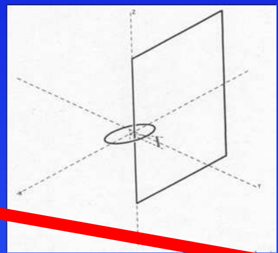
Ikuta Torus (K.Ikuta, 1968)



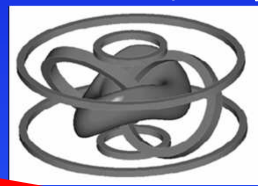
Cleftron (T.Ohkawa, 1981)

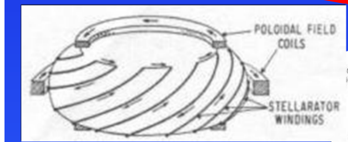


Ultra SimpleStellarator (T.Todd,1990)

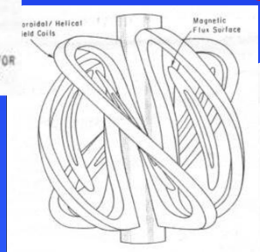


CNT (T.S.Pedersen & A.H.Boozer, 2002)

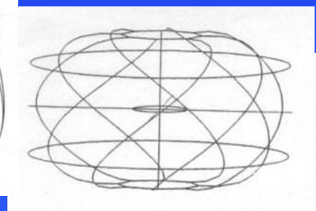




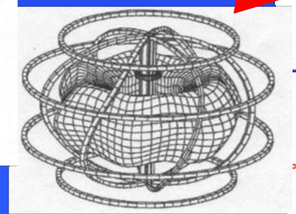
Strong Negative V'' (H.P.Furth et al., 1968)



Tokatron (H.P.Furth et al., 1981)

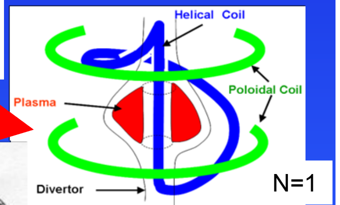


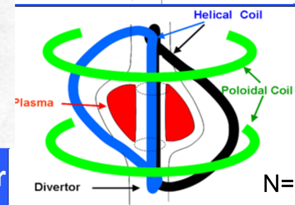
Tokastar (K.Yamazaki, 1985)



Spherical Stellarator (P.E.Moroz, 1996)

C-Tokastar (K.Yamazaki,2004)





- Several low aspect-ratio helical systems have been created for compact and low-cost designs of fusion reactor

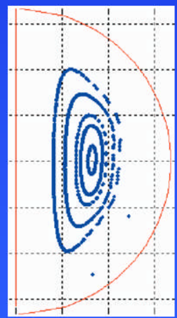
- One of the authors (K. Y.) proposed the tokamak-stellarator hybrid concept called TOKASTAR.

TOKASTAR configuration

Advantages

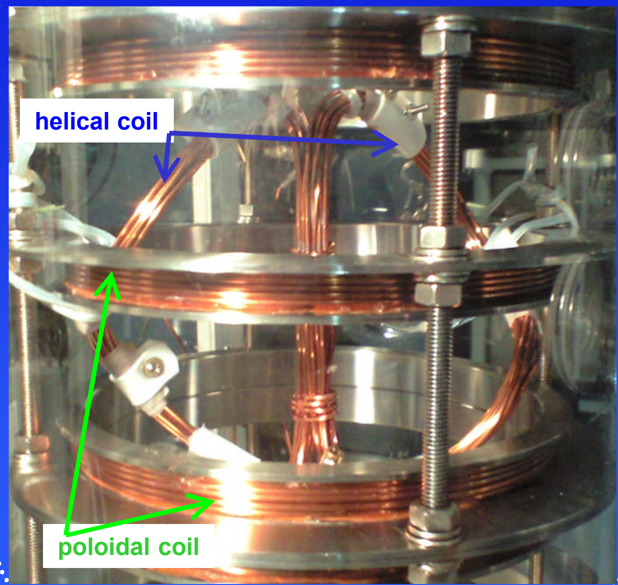
- Steady-state operation by helical coils
- No current disruption risk
  by external helical field application
- The rotational transform can be increased by inducing plasma current
- Enough diverter space and easy maintenance by simple N=1 or N=2 coil system
- Compact economic system
  by spherical configuration

Existence of the vacuum magnetic surface was confirmed experimentally in C-TOKASTAR device.



Y. Taira et al, Plasma and Fusion Res. **5**, S1025 (2010)

C-TOKASTAR device



➢ Investigation of the relationship among the plasma current, helical magnetic configurations and confinement property is needed. ⇒ New device “TOKASTAR-2”

2. TOKASTAR-2 device

Motivation and reseach plans of TOKASTAR-2

- To evaluate the effect of outer helical field application on tokamak plasma.
- To generate low aspect ratio current-less helical plasma.

Flow chart of the study and Topics to be presented in this presentation

ECR plasma production as a pre-ionized phase of tokamak operation

↓

Plasma current start-up experiments
- **Plasma current induction using OH coil system**

Design of helical plasma & coils
- **Calculation of magnetic surface by magnetic line tracing analysis**

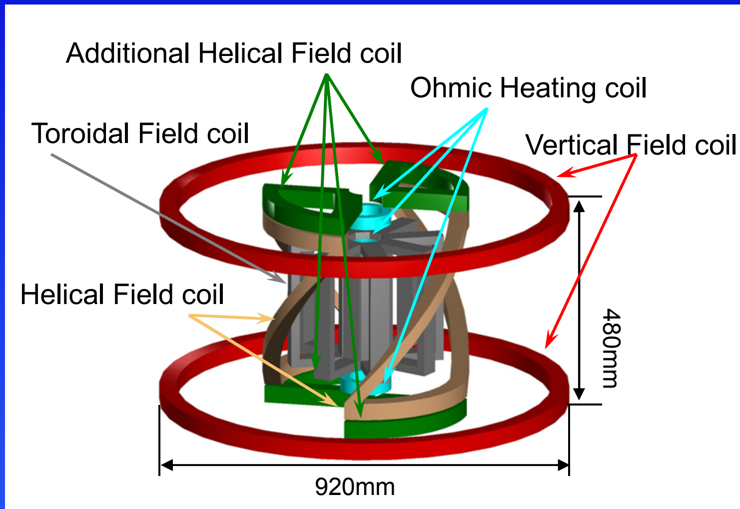
↓

Current-less helical plasma production

↓

Investigation of the characteristics of tokamak-helical hybrid plasmas

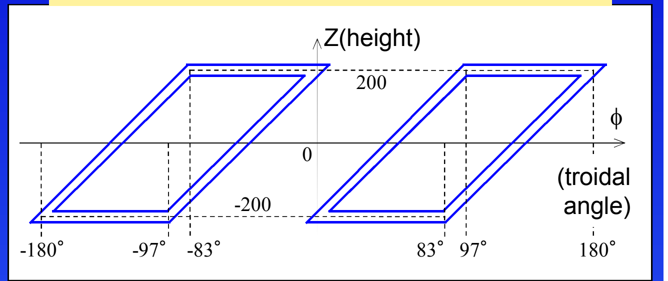
Overview of TOKASTAR-2 device



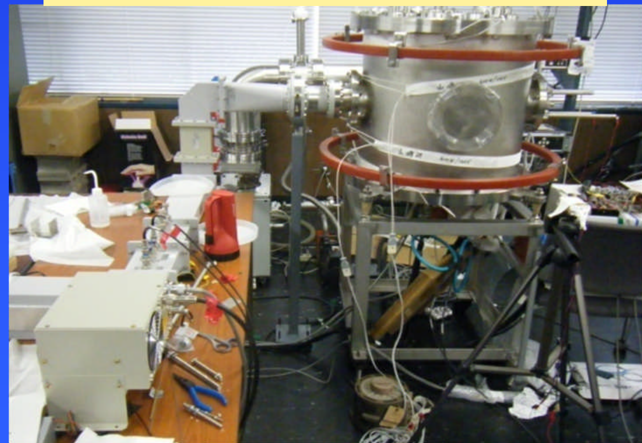
- Working gas : He or H_2
- Base pressure : ~10^{-3}Pa
- Experiment region of gas pressure
  : 0.01~0.5Pa
- Power supply to TF and OH coils
  : 200 μF capacitor x1~4 units
  (stored voltage < 2.0 kV)

AHF coils have not been constructed.

φ-Z view of the helical field coils



The experimental set-up

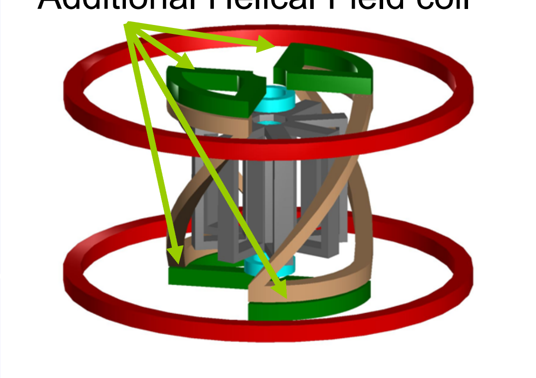


Start-up: ECH by 2.45 GHz RF (< 2.0 kW)

3. Magnetic line tracing analysis of helical plasma

The formation of the vacuum magnetic surfaces by optimizing the additional helical field coils.

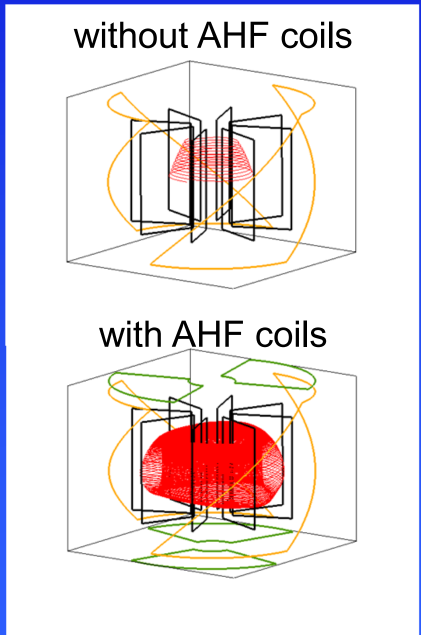
In this section, below 6 topics are explained.

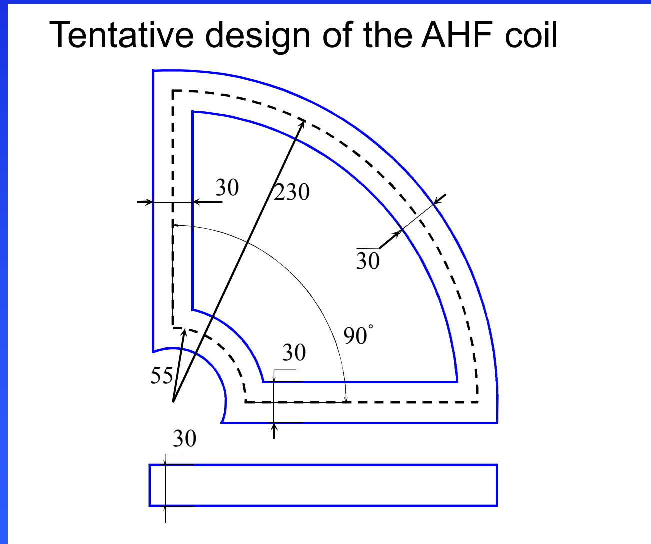


3.1 Additional Helical Field coil
3.2 Requirements for AHF coils and helical plasma
3.3 Evaluation about set-up angle of AHF coils
3.4 Variation of averaged radius with different coil current ratios
3.5 Control of the location of magnetic surface with varying coil current ratio
3.6 Profiles of rotational transform and magnetic surface

3.1 Additional Helical Field coil

Additional helical field coils are needed to form the vacuum magnetic surface without plasma current. It is revealed by calculation of magnetic line tracing.
The position of AHF coil is 0.03m separated from helical field coil vertically.

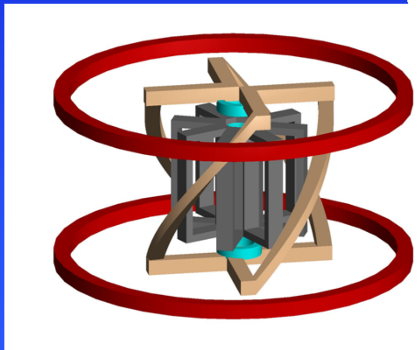




There are several requirements which AHF coil and helical plasma should satisfy.

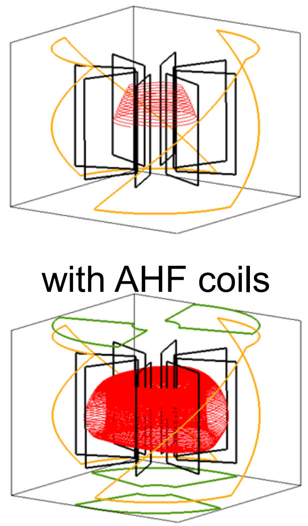
3.1 Additional Helical Field coil

Once, we planned to construct "Original HF coil". However, there were several problems to construct it. Then Original HF coil divided to present HF and AHF coil. Additional helical field coils are needed to form the vacuum magnetic surface without plasma current. It is revealed by calculation of magnetic line tracing.

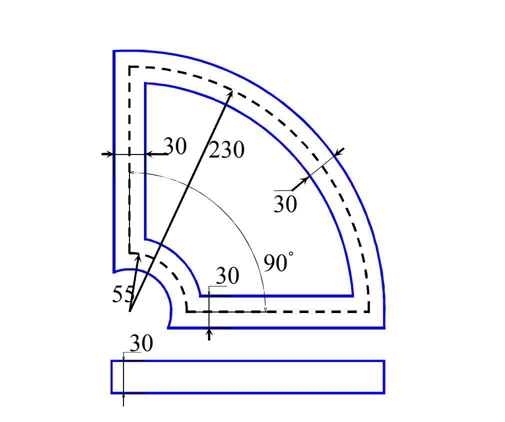


without AHF coils

with AHF coils



Tentative design of the AHF coil



The position of AHF coil is 0.03m separated from helical field coil vertically.

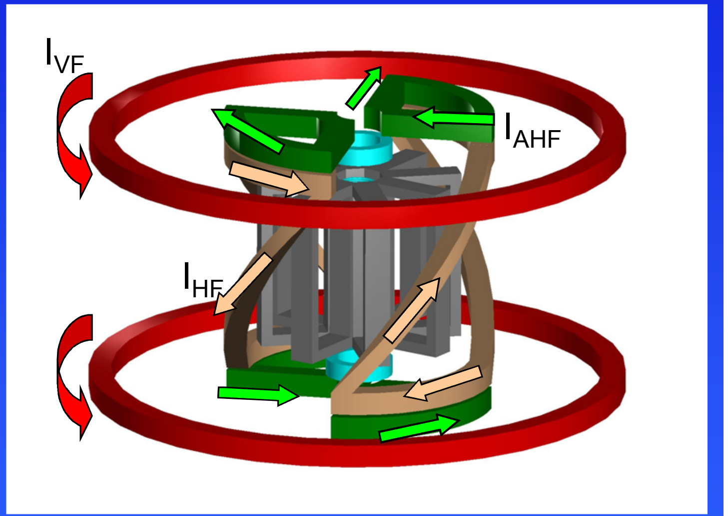
There are several requirements which AHF coil and helical plasma should satisfy.

3.2 Requirements for AHF coils and vacuum magnetic surface

Vacuum magnetic surface

- To be located near the mid plane.
- To obtain sufficient size of magnetic surface.
- Current values of AHF and HF coil (I_{AHF} and I_{HF}) are as low as possible.

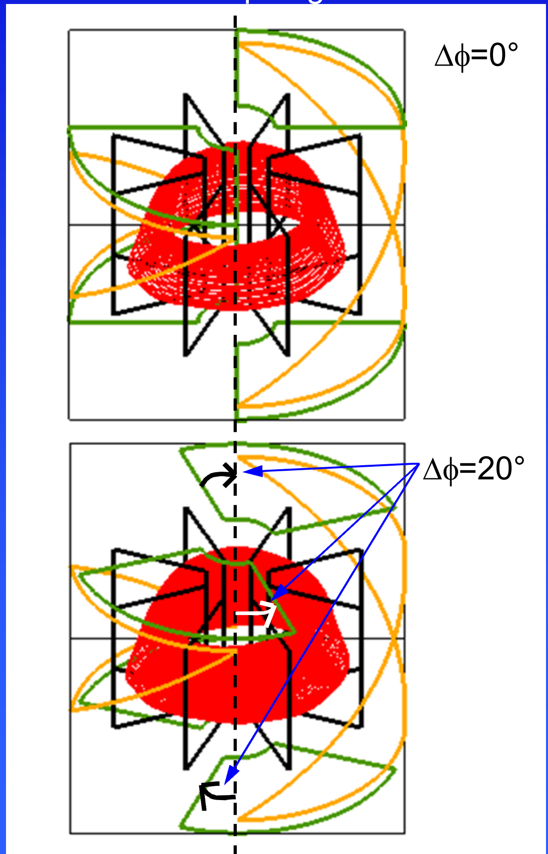
Coil current direction



Using magnetic line tracing analysis, we compared averaged radius of the last closed flux surface varying set-up angle and coil current ratio satisfying above requirements.

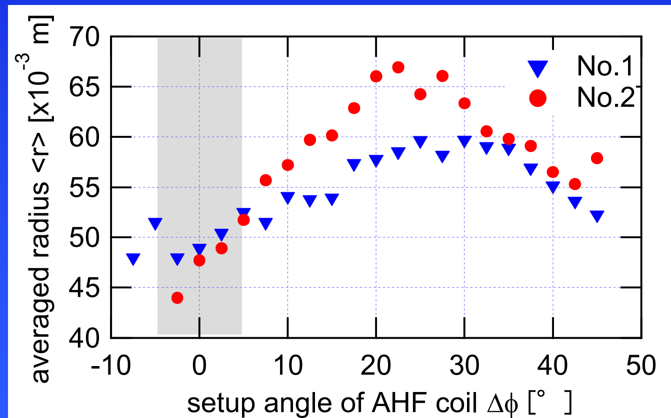
3.3 Evaluation of set-up angle of AHF coils

Definition of set-up angle of AHF coil Δϕ

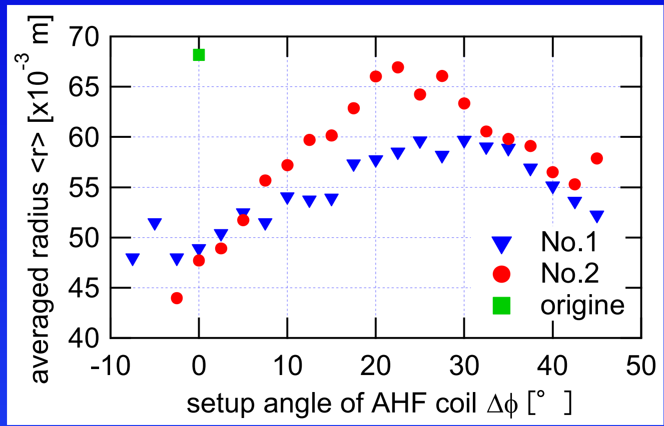


Used coil current ratio patterns

	I_{AHF}/I_{HF}	I_{TF}/I_{HF}	I_{VF}/I_{HF}
No.1	1.4	0.86	0.14
No.2	1.5	0.62	0.12



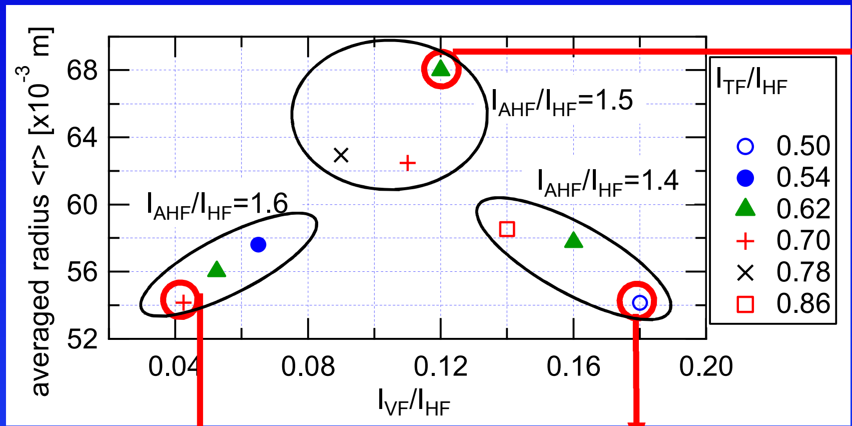
- Averaged radii in region between 15~40° are greater than those in ~0°.
- Considering this result and arrangement of supporting structures for AHF coils, we decided to set up AHF coils at Δϕ=22.5°.



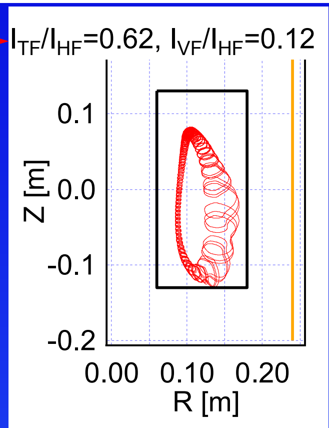
averaged radius <r> [x10^{-3} m]
70
65
60
55
50
45
40
-10
0
10
20
30
40
50
setup angle of AHF coil Δφ [°]
No.1
No.2
origine

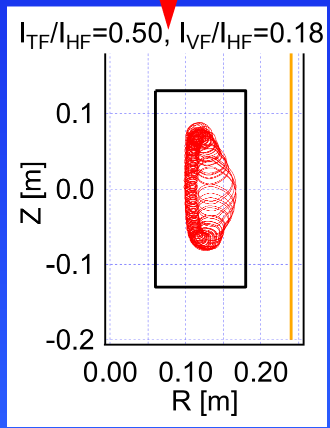
3.4 Variation of averaged radius with different coil current ratios

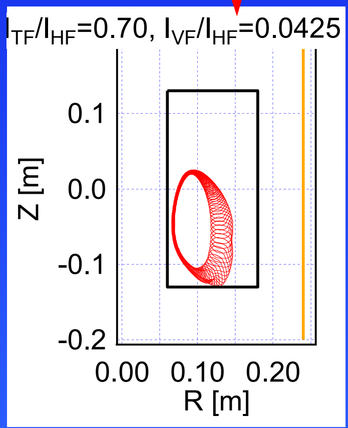
Peak values varying coil current ratios



toroidal projected view

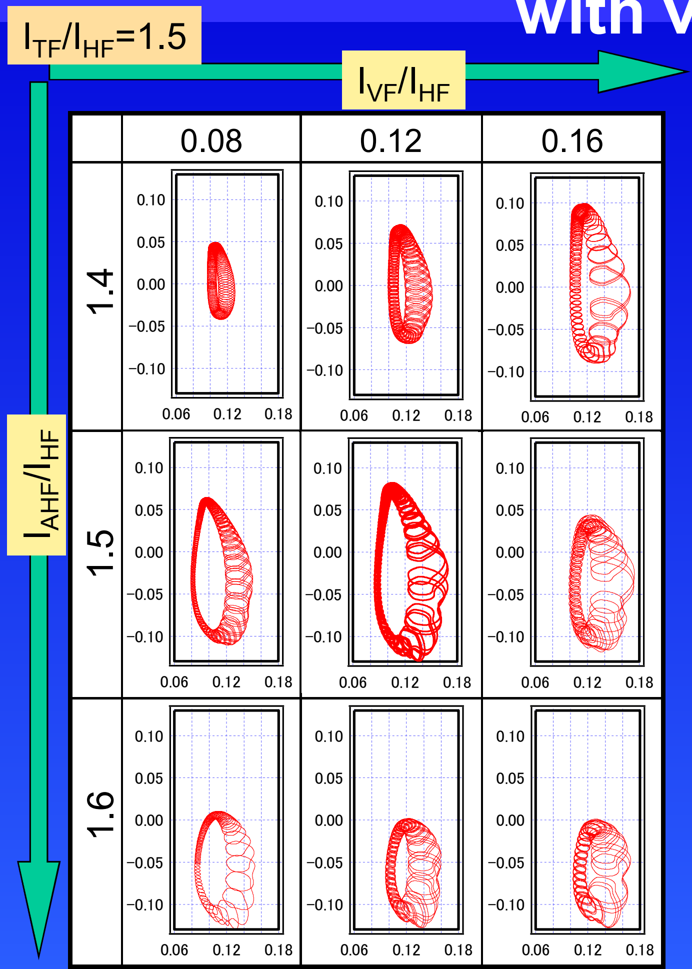






- The largest averaged radius is obtained at I_{AHF}/I_{HF}=1.5, I_{TF}/I_{HF}=0.62 and I_{VF}/I_{HF}=0.12.
- It is revealed locations of magnetic surface are different from each other.

3.5 Control of the location of magnetic surface with varying coil current ratio



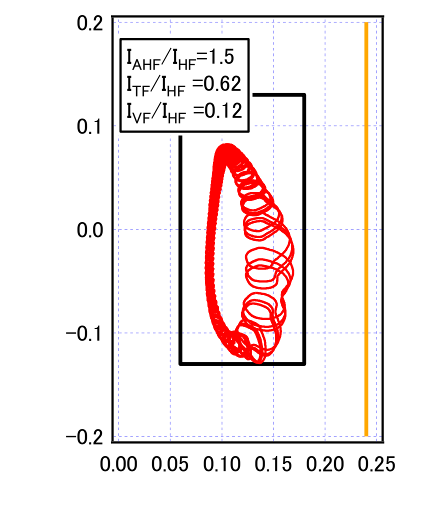
We kept I_{TF}/I_{HF}=1.5 (constant) and varied I_{AHF}/I_{HF} and I_{VF}/I_{HF}.

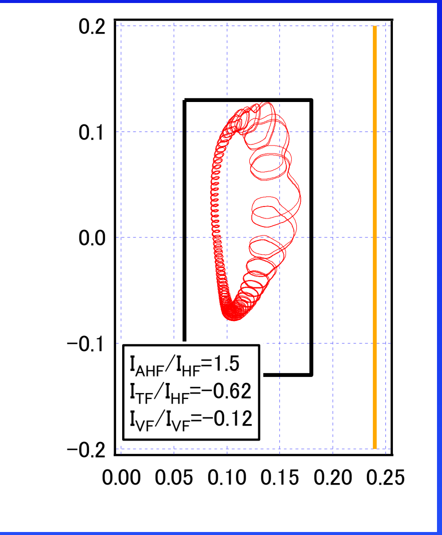
- As additional helical field increases, magnetic surfaces are located vertically downward.
- As vertical field increases, magnetic surfaces are located horizontally outboard.

From this result, it is clarified that the location of plasma can be controlled with adjusting coil current ratios.

The magnetic surface located upward vertically

	I_{HF}[AT]	I_{AHF}[AT]	I_{TF}[AT]	I_{VF}[AT]
Downward	10000	15000	6200	1200
Upward	-10000	-15000	6200	1200



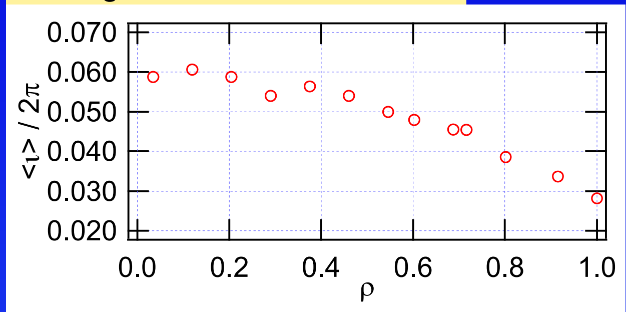


The magnetic surface can be located upward vertically with reversing current directions of AHF and HF coils.

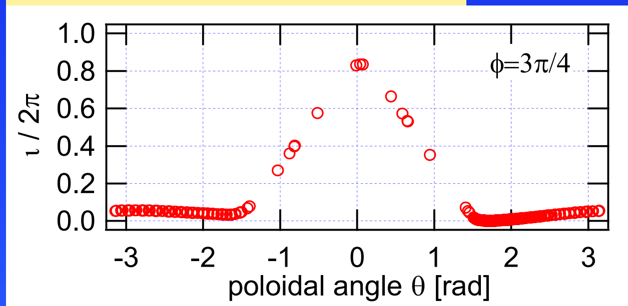
3.6 Profiles of rotational transform and magnetic surface

Obtained largest last closed magnetic surface (I_{AHF}/I_{HF}=1.5, I_{TF}/I_{HF}=0.62 and I_{VF}/I_{HF}=0.12)

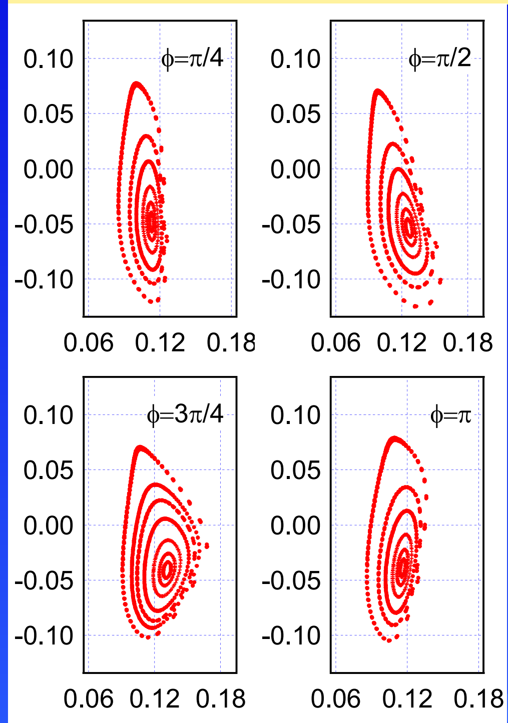
Radial profile of averaged rotational transform



Polodal profile of local rotational transform



Poloidal closs section of closed vacuum flux surfaces



Averaged rotational toransform is low, however, the outboard local rotational transform is large.

4. Trial of the tokamak operation

Experimental condition

- P_{He}~10^{-2}Pa
- P_{RF}=0.8kW(2.45GHz)
- B_t=0.0875T at R~0.08m
  (pulse discharge to TF coils
  using a 200μF capacitor unit)
- B_V=1.5mT
  (DC power supply to VF coils)
- V_{loop}~4V
  (pulse discharge to OH coils
  using 200μF capacitor x4 units)

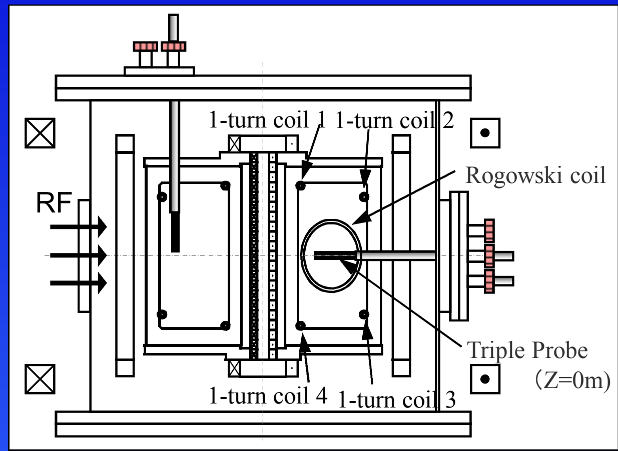
Measurement devices

Rogowski coil, Triple probe,

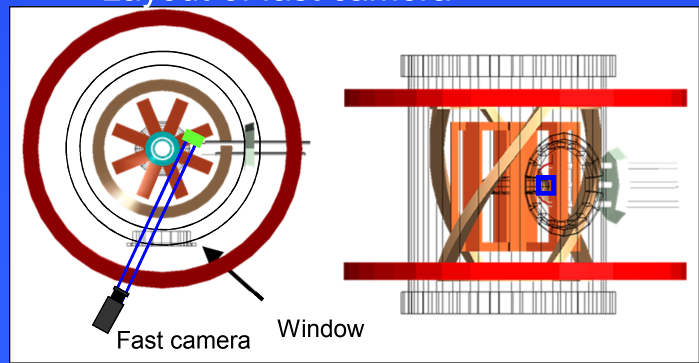
Fast camera (20500fps),

Avalanche Photodiode Detector (APD)

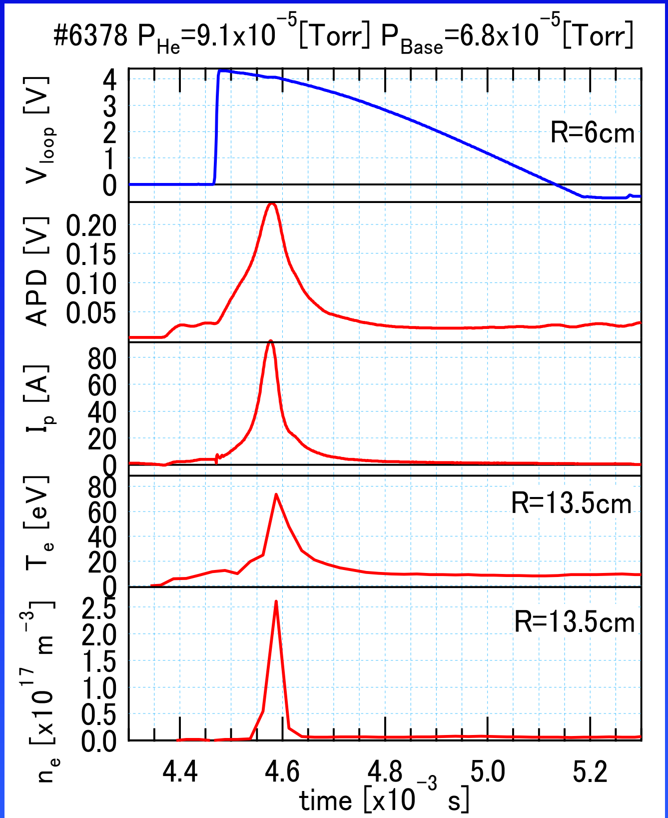
Cross sectional view of TOKASTAR-2



Layout of fast camera



Typical waveform of the tokamak discharge



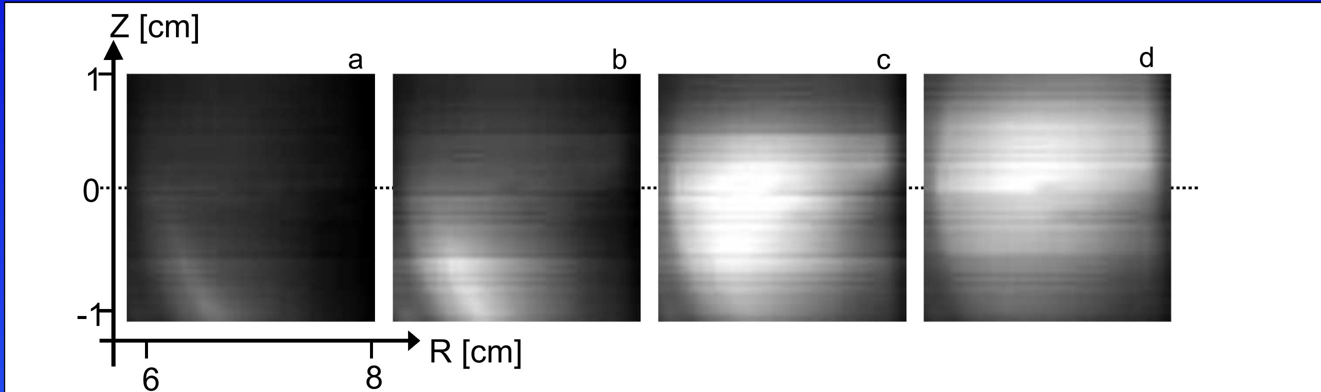
- Each values increase after onset of the loop voltage.
- Especially, the electron density exceeds the cut-off density. ($0.7 \times 10^{17} m^{-3}$ in TOKASTAR-2)
- However, the plasma current of only 90A is obtained.

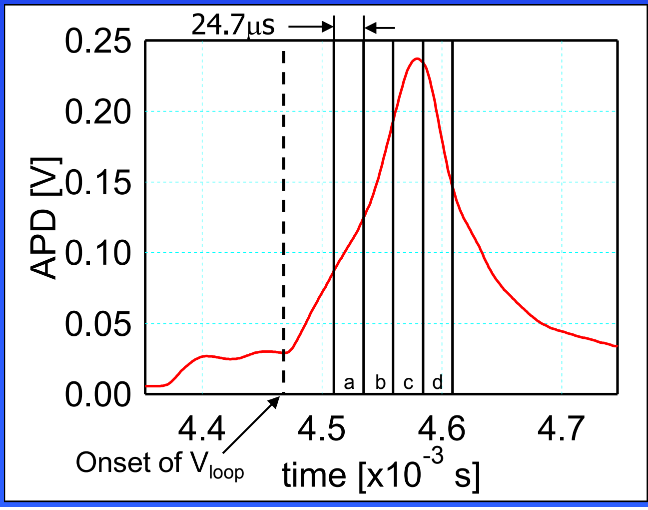
◆ The static vertical field is inappropriate to suppress the horizontal displacement due to time-varying hoop force.

◆ Error field by eddy current induced in vacuum chamber is also cause of that displacement.

Consecutive photographs of plasma by fast camera

In addition, a vertical displacement of plasma was also observed experimentally.





The plasma moved vertically upward.

- Due to up-down unbalance of induced eddy current and applied static vertical field.
- The error field by OH coils keeps N-value negative at inboard.

It is considered this movement interferes the increase the plasma current.

Summary

- New torus plasma confinement device having tokamak-helical hybrid magnetic configuration “TOKASTAR-2” was constructed.
- It can apply outer helical field on tokamak plasma by using a pair of helical field coils. And it can generate current-less helical plasma by using two pair of additional helical field coils.

- From magnetic line tracing analysis, we decided to set up AHF coils at $\Delta\phi=22.5°$.
- It is clarified that controlling the location of magnetic surface is possible by adjusting coil current ratios.

- Ohmic heating was applied to induce plasma current, however, it was obtained only 90A. From photographs taken by fast camera, it was clarified that OH plasma moved vertically upward.

Future plans

- We plan to establish the existence of ECR layer in helical configuration within limitation of power supplies, and to construct AHF coils as soon as possible.

- Using static vertical field due to limitation of power supplies can not induce more than 0.1kA plasma current.
  Then we plan to install VF coils inside the vacuum chamber. Then we have been designing new VF coils which have appropriate turn number and the inductance for pulsed discharge system.

We believe that results of these experiments will be useful for the development of compact torus.

Summary and future plans

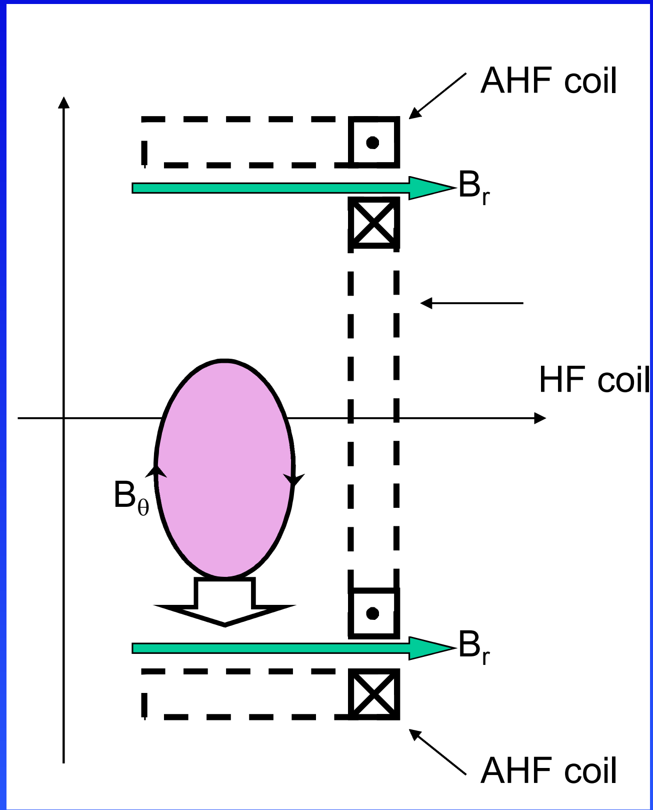
- TOKASTAR-2 can apply outer helical field on tokamak plasma by using a pair of helical coils. And it can generate current-less helical plasma by using two pair of additional helical coils.

- From magnetic line tracing analysis, it is clarified that controlling the location of magnetic surface is possible by adjusting coil current ratios.
- We plan to establish the existence of ECR layer in helical configuration within limitation of power supplies, and to construct AHF coils as soon as possible.

- The plasma current was obtained only 90A using ohmic heating. From photographs taken by fast camera, it was clarified that OH plasma moved vertically upward.
- We plan to install VF coils inside the vacuum vessel. Then we have been designing new VF coils which have appropriate turn number and the inductance for pulsed discharge system.

We believe that results of these experiments will be useful for the development of compact torus.

The reason why magnetic surface becomes asymmetry



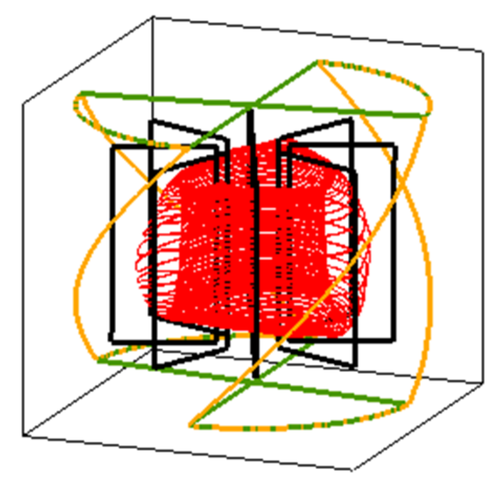
The vertical asymmetry of magnetic surface is due to the gap between AHF coil and HF coil.

This gap makes the horizontal field and magnetic axis is shifted vertically.

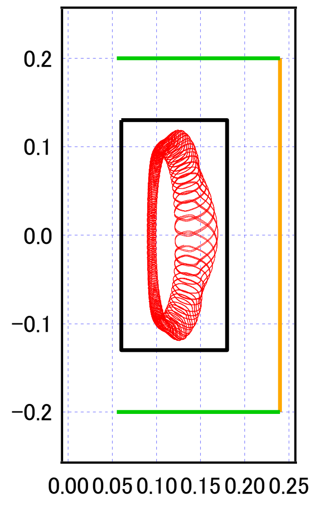
Magnetic surface without the gap

The magnetic surface becomes symmetry if thicknesses of coils are ignored and AHF coils overlap with HF coils.

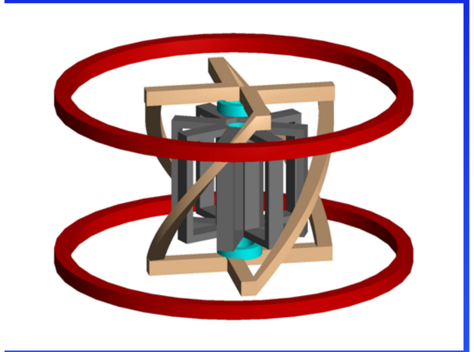
Bird's eye view

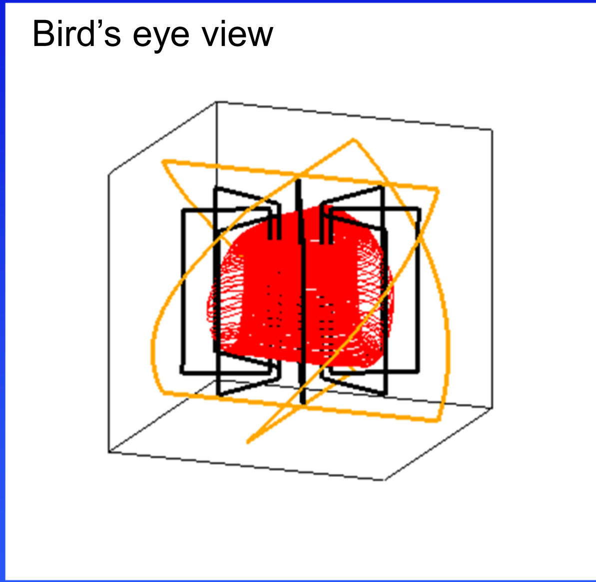


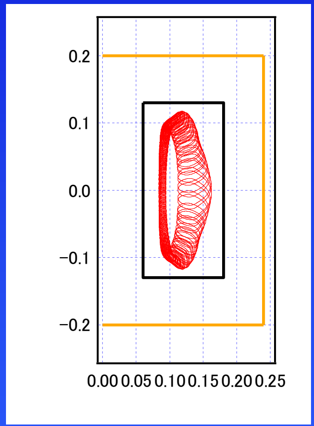
Toroidal projected view



Original HF coil system

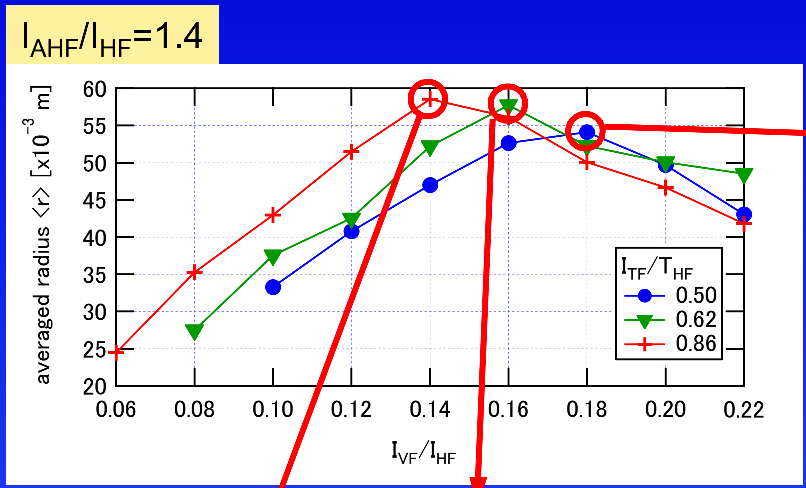


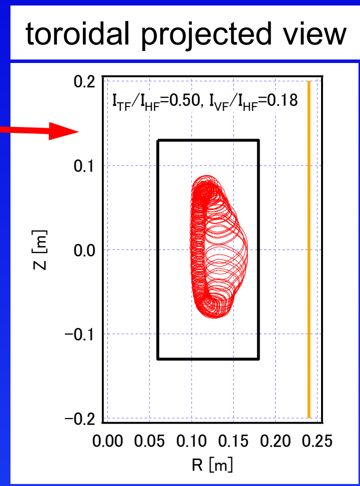


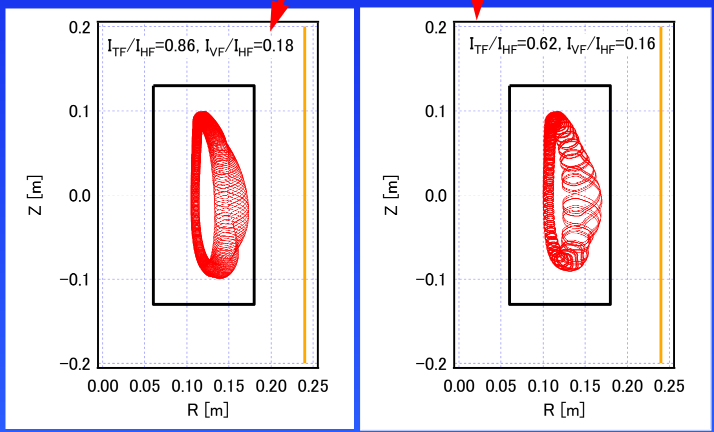


- Essentially, HF coil should unite with AHF coil.
- Because there were several problems to construct original HF coils, it was divided to present HF coil and AHF coil.

Variation of averaged radius with different coil current ratios 1/3

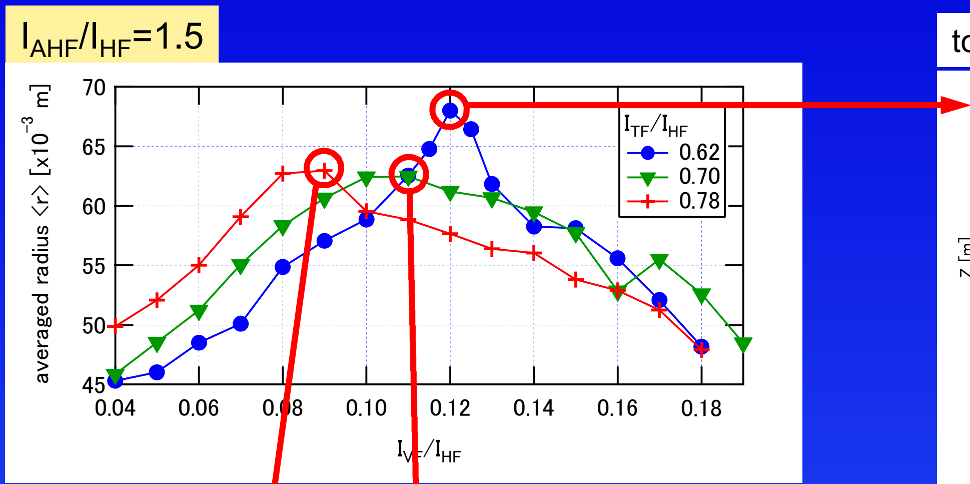


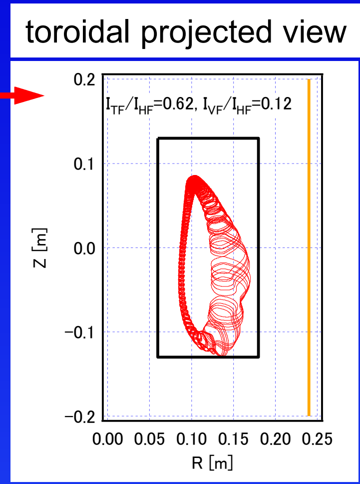


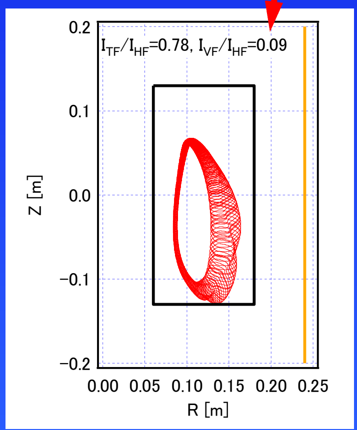


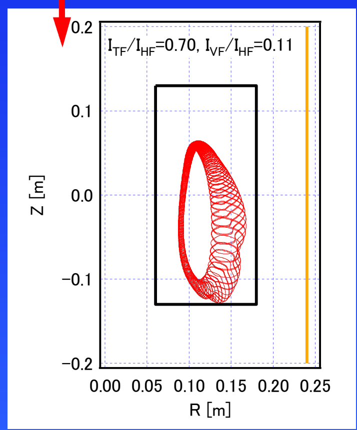
- There is an increase in the peak of averaged radius with increasing of toroidal field.
- The magnetic surface is located near the equatorial plane.

Variation of averaged radius with different coil current ratios 2/3



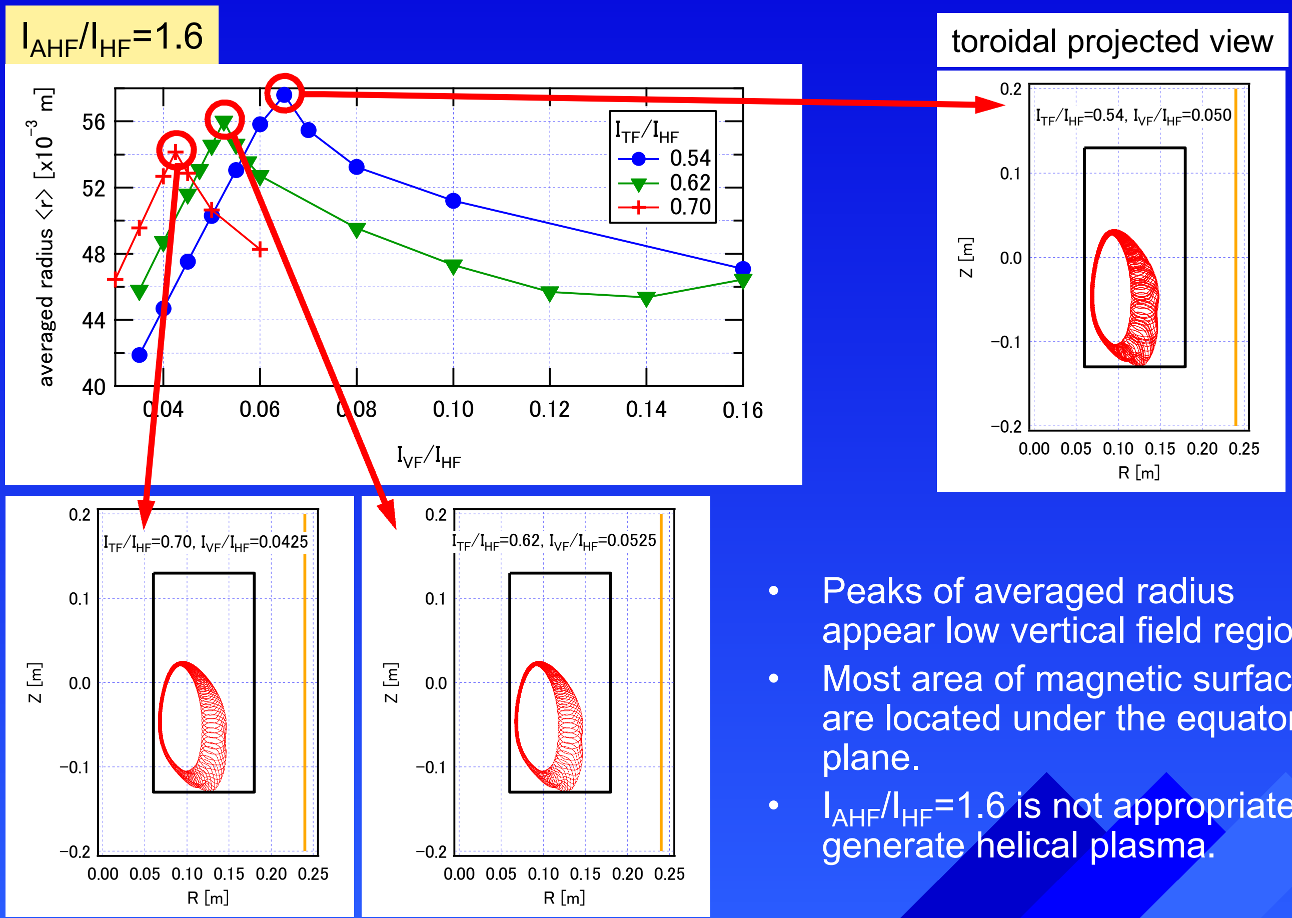






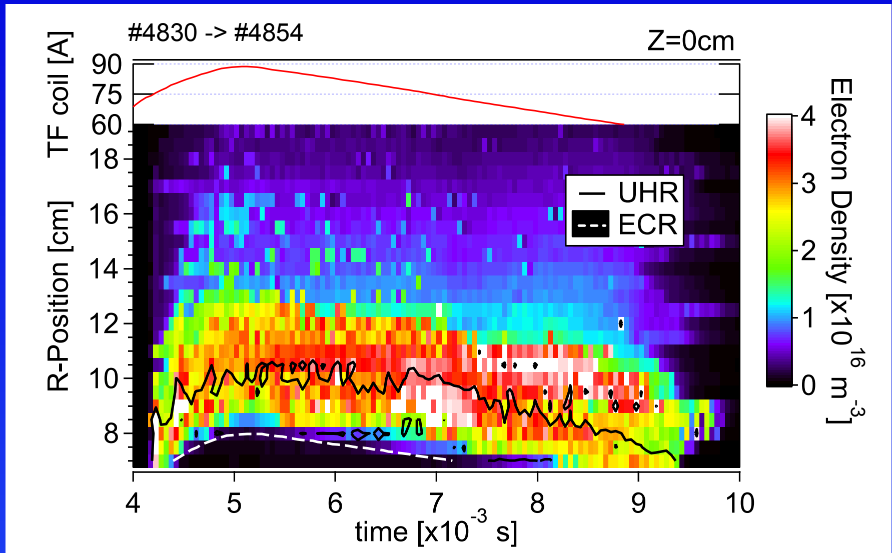
- The largest averaged radius is obtained at I_{TF}/I_{HF}=0.62 and I_{VF}/I_{HF}=0.12.

Variation of averaged radius with different coil current ratios 3/3



- Peaks of averaged radius appear low vertical field region.
- Most area of magnetic surface are located under the equatorial plane.
- I_{AHF}/I_{HF}=1.6 is not appropriate to generate helical plasma.

Radial profile of ECR plasma

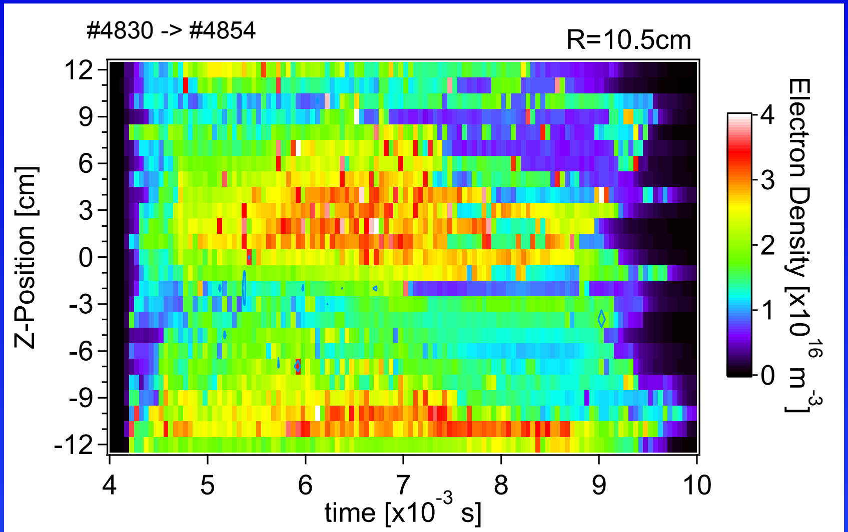


The plasma is initiated near the ECR layer

The UHR layer corresponds with the peak.

⇒ It is considered the plasma production and sustainment are mainly due to UHR.

Vertical profile of ECR plasma



Main plasma profile shifted vertically upward.

It is considered due to the influence of error field.

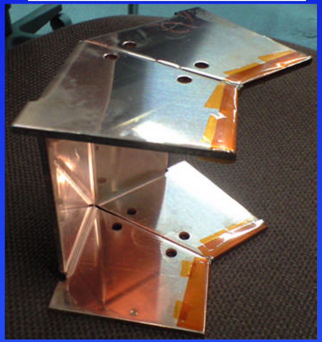
There are two dense regions above (Z>12cm) and below (Z~-10cm) the main plasma.

It is supposed these plasmas are produced by the ECR and UHR close to upper and bottom walls of TF coil.

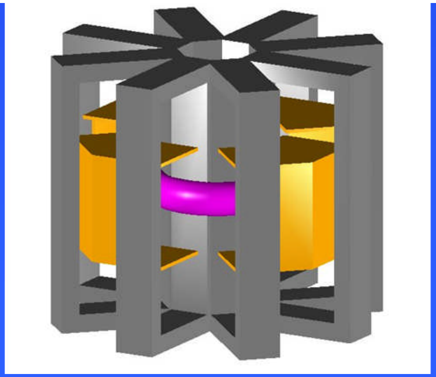
The effect of conductive shell

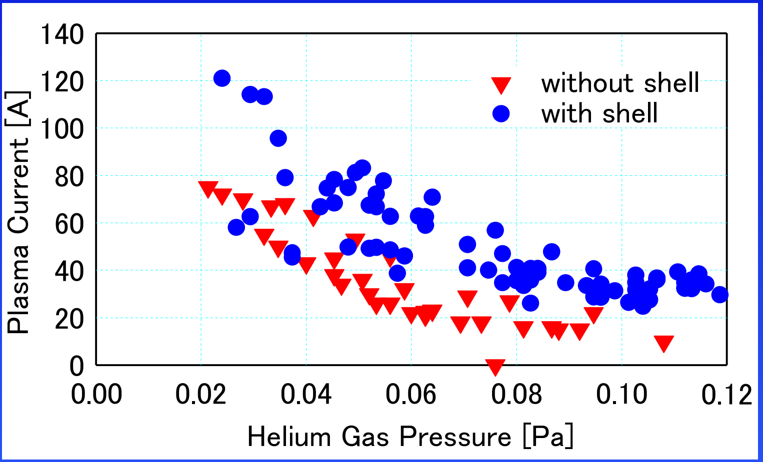
To suppress the vertical movement of the plasma, conductive shell was constructed.

a part of the shell



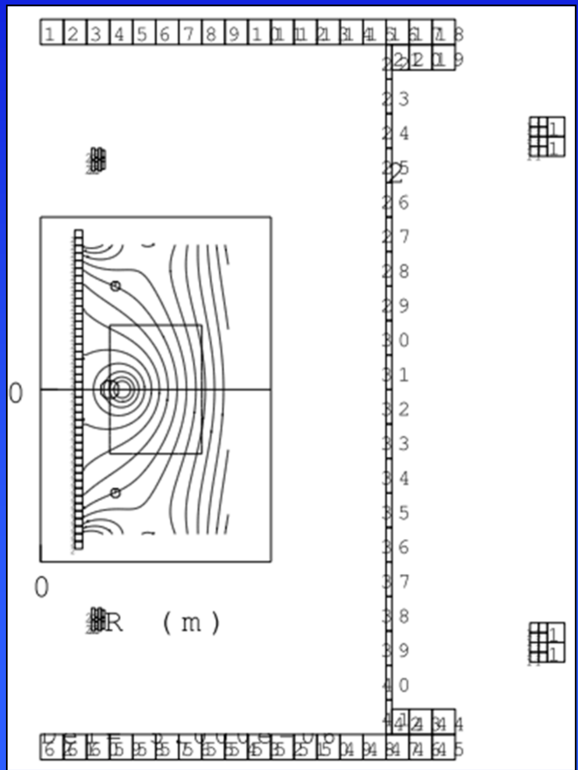
configuration of the shell and TF coils

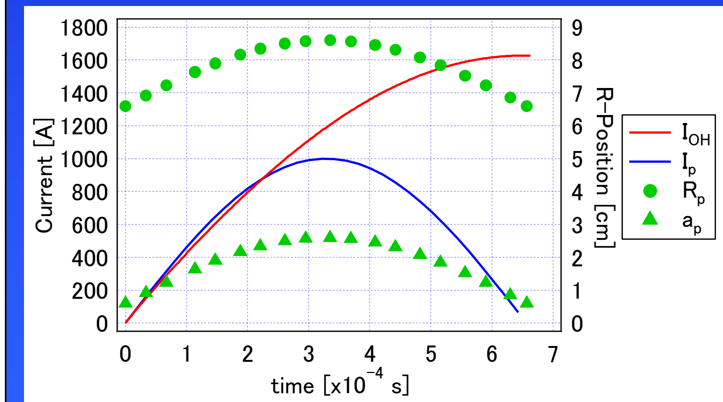


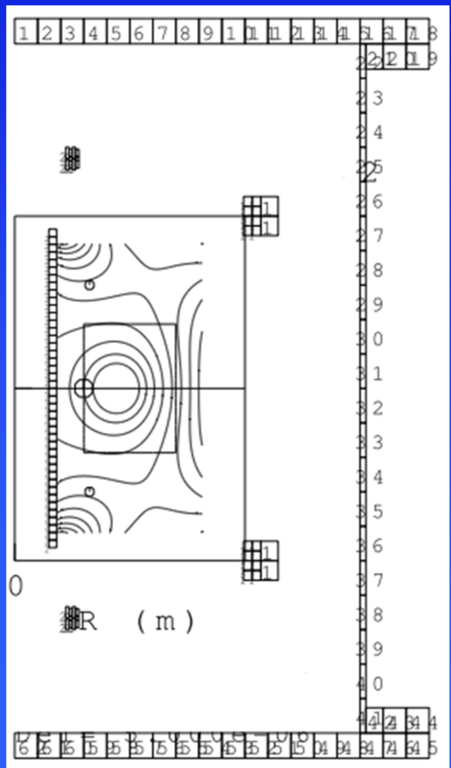


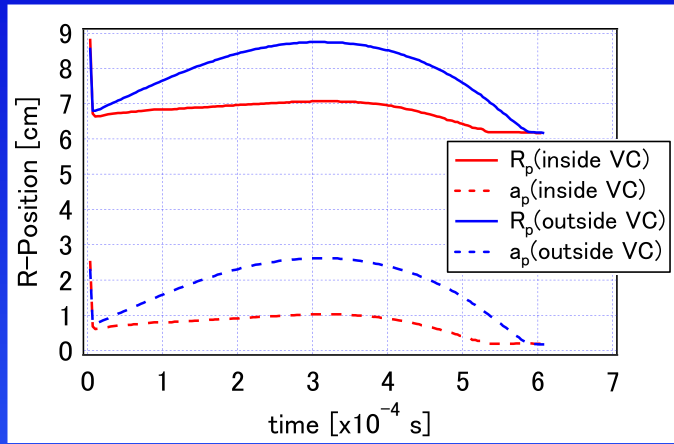
- Although the plasma current reaches up to 120A, it does not greatly increase.
- The effect of suppressing vertical movement has not been confirmed yet.

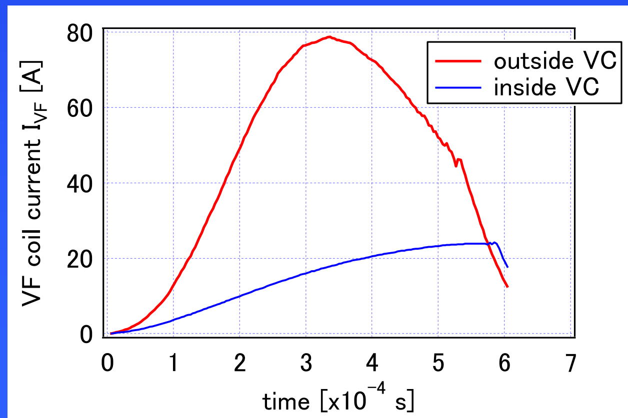
Optimization of VF coil current






R (m)


R−Position [cm]
time [x10^{-4} s]
R_p(inside VC)
a_p(inside VC)
R_p(outside VC)
a_p(outside VC)


VF coil current I_{VF} [A]
time [x10^{-4} s]
outside VC
inside VC